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(54) **HIGHER ORDER MULTIPLE INPUT MULTIPLE OUTPUT IN ETHERNET**

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H04B 3/32	(2006.01)
H01B 11/12	(2006.01)

(52) **U.S. Cl.**
CPC ***H04B 3/50*** (2013.01); ***H01B 11/12*** (2013.01); ***H04B 3/32*** (2013.01)

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USPC 375/257–260, 295, 316
See application file for complete search history.

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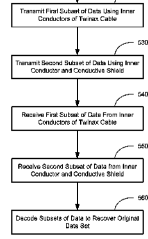
(57) **ABSTRACT**

A method of MIMO signal transmission on a cable is disclosed. The cable includes at least a first inner conductor, a second inner conductor, and an outer conductive shield. A first data signal is transmitted using the conductive shield and the first inner conductor. A second data signal is transmitted using at least the second inner conductor. The first and second data signals may be transmitted concurrently. For some embodiments, the second data signal may be transmitted using the first and second inner conductors. Thus, the second data signal may be a differential signal. For other embodiments, the first data signal may be transmitted using the conductive shield and the first inner conductor, and the second data signal may be transmitted using the conductive shield and the second inner conductor.

30 Claims, 13 Drawing Sheets



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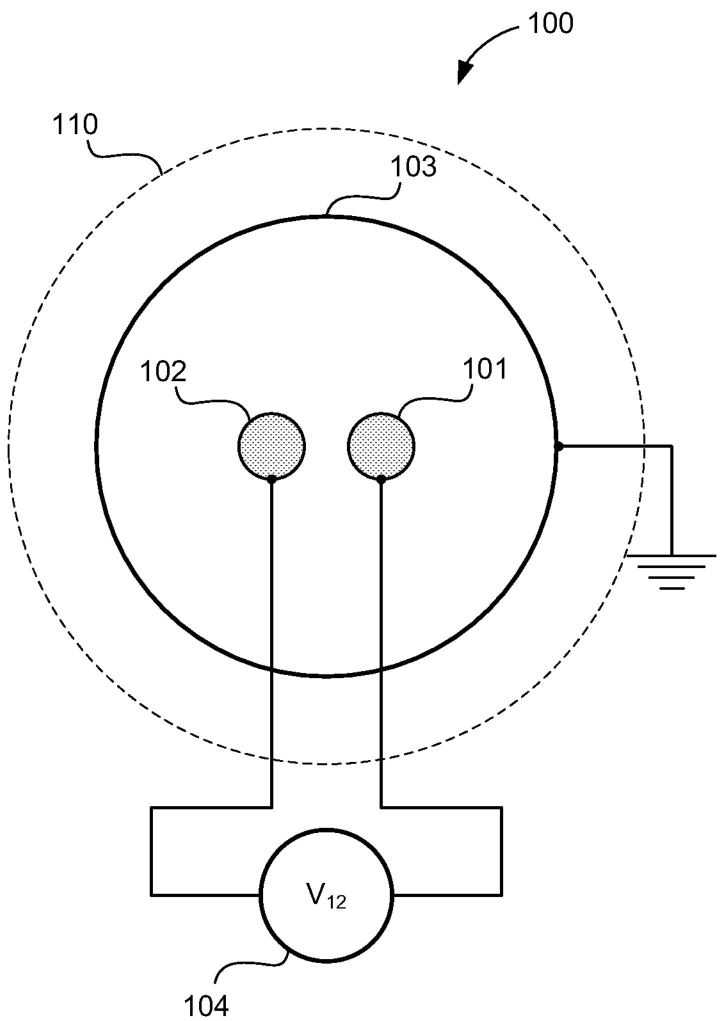


FIG. 1

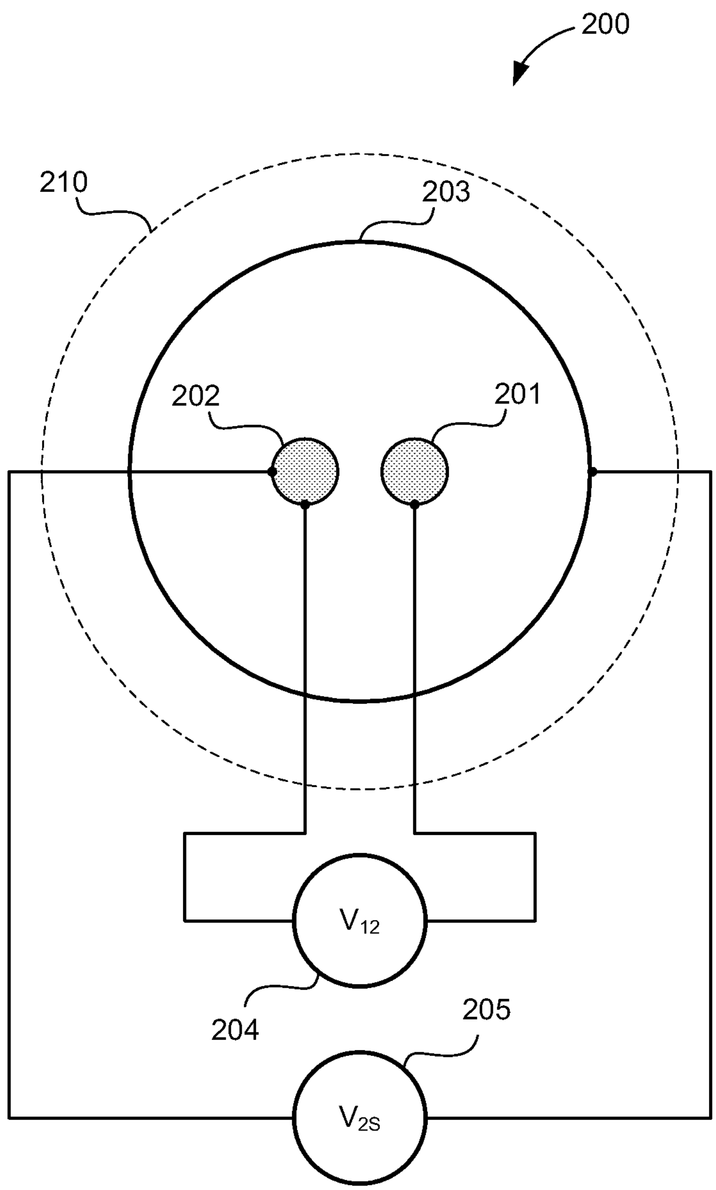


FIG. 2

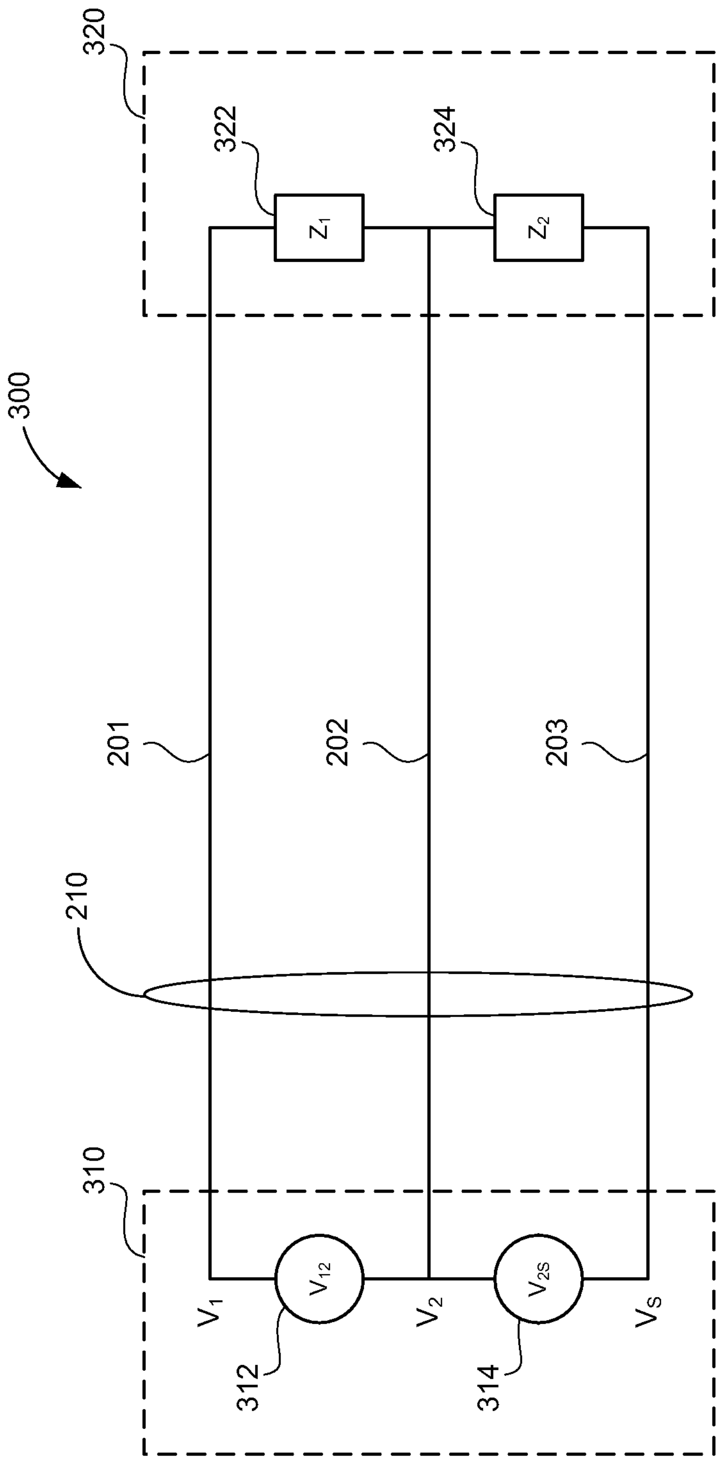


FIG. 3

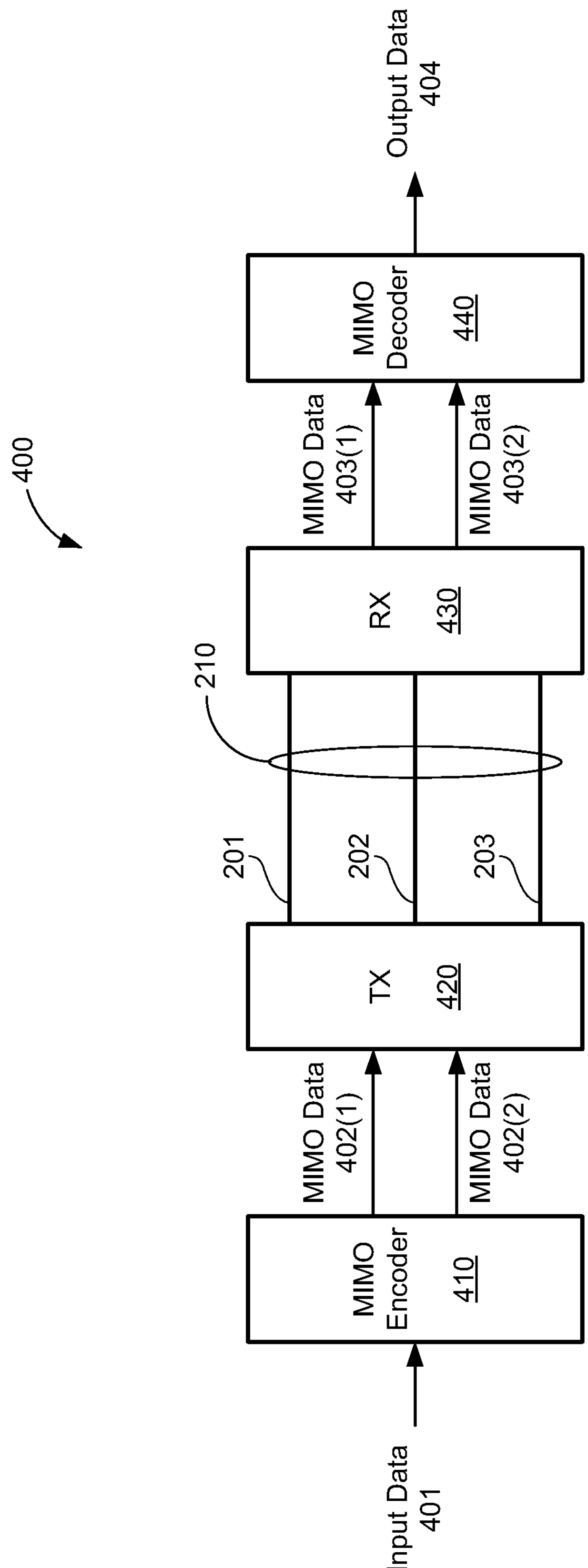

400
Input Data
401
MIMO
Encoder
410
MIMO Data
402(1)
MIMO Data
402(2)
TX
420
201
202
203
210
RX
430
MIMO Data
403(1)
MIMO Data
403(2)
MIMO
Decoder
440
Output Data
404

FIG. 4

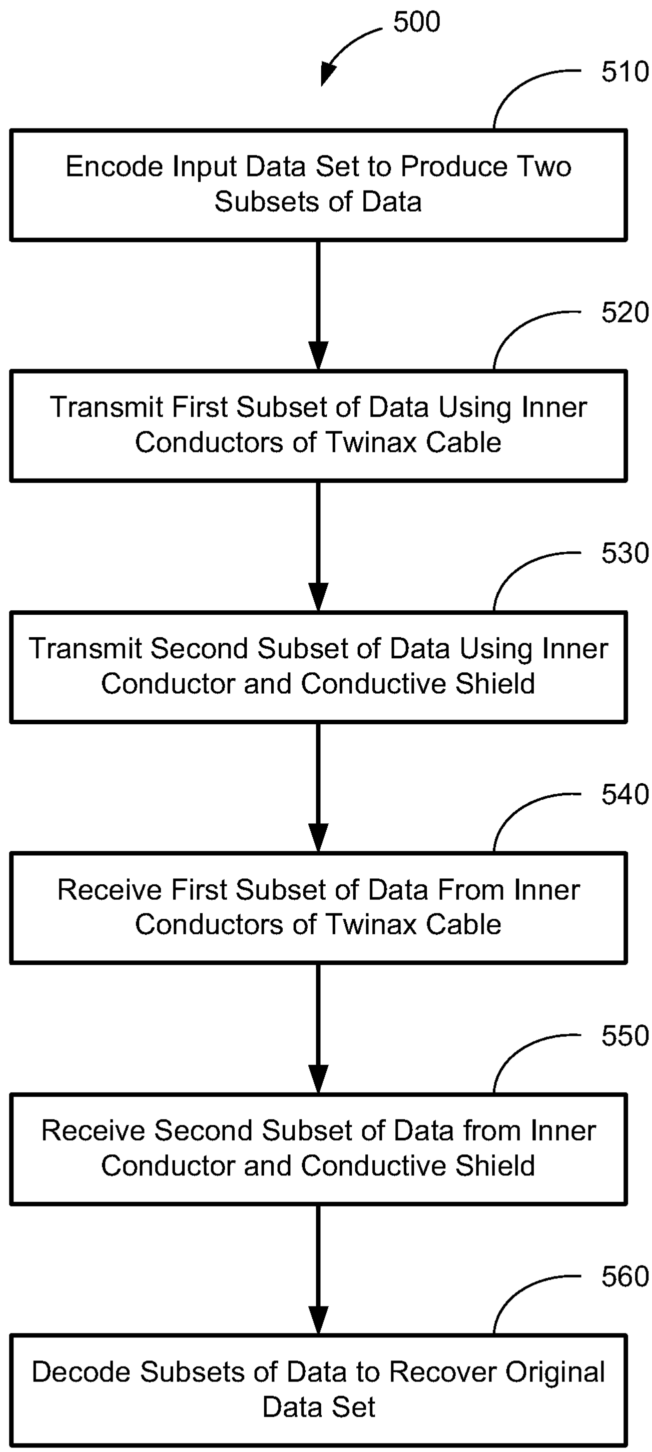

500
510
Encode Input Data Set to Produce Two Subsets of Data
520
Transmit First Subset of Data Using Inner Conductors of Twinax Cable
530
Transmit Second Subset of Data Using Inner Conductor and Conductive Shield
540
Receive First Subset of Data From Inner Conductors of Twinax Cable
550
Receive Second Subset of Data from Inner Conductor and Conductive Shield
560
Decode Subsets of Data to Recover Original Data Set

FIG. 5

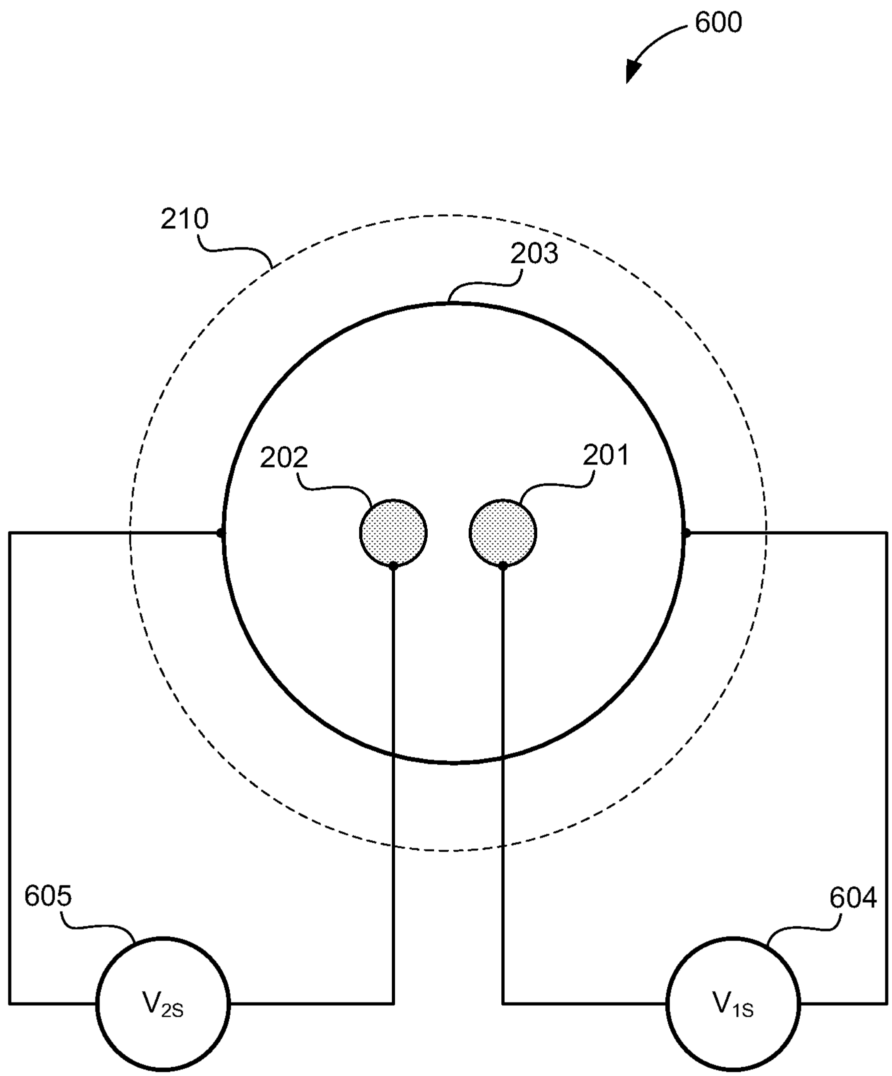
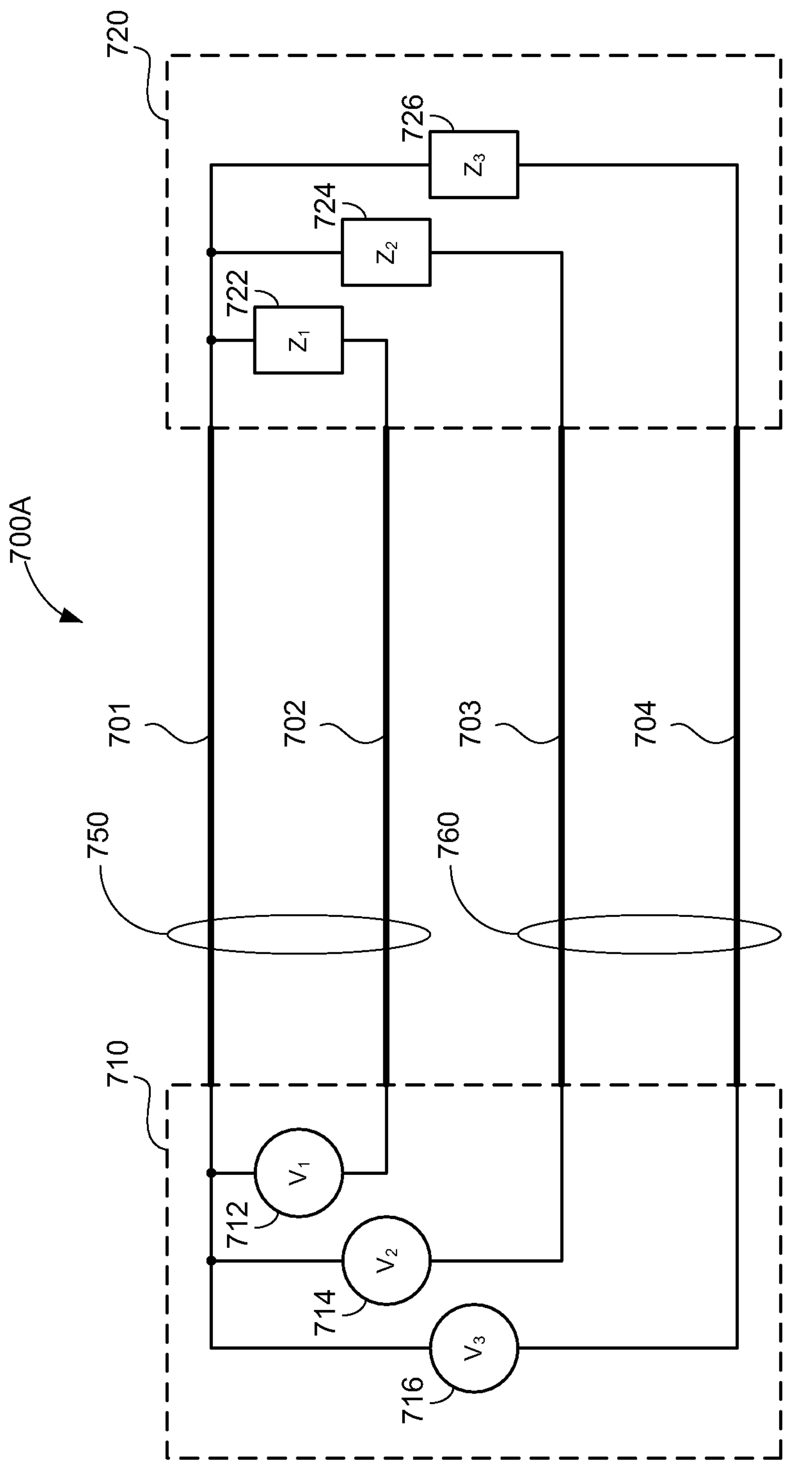


FIG. 6



720
726
Z_3
724
Z_2
722
Z_1
700A
701
702
703
704
750
760
710
V_1
712
V_2
714
V_3
716

FIG. 7A

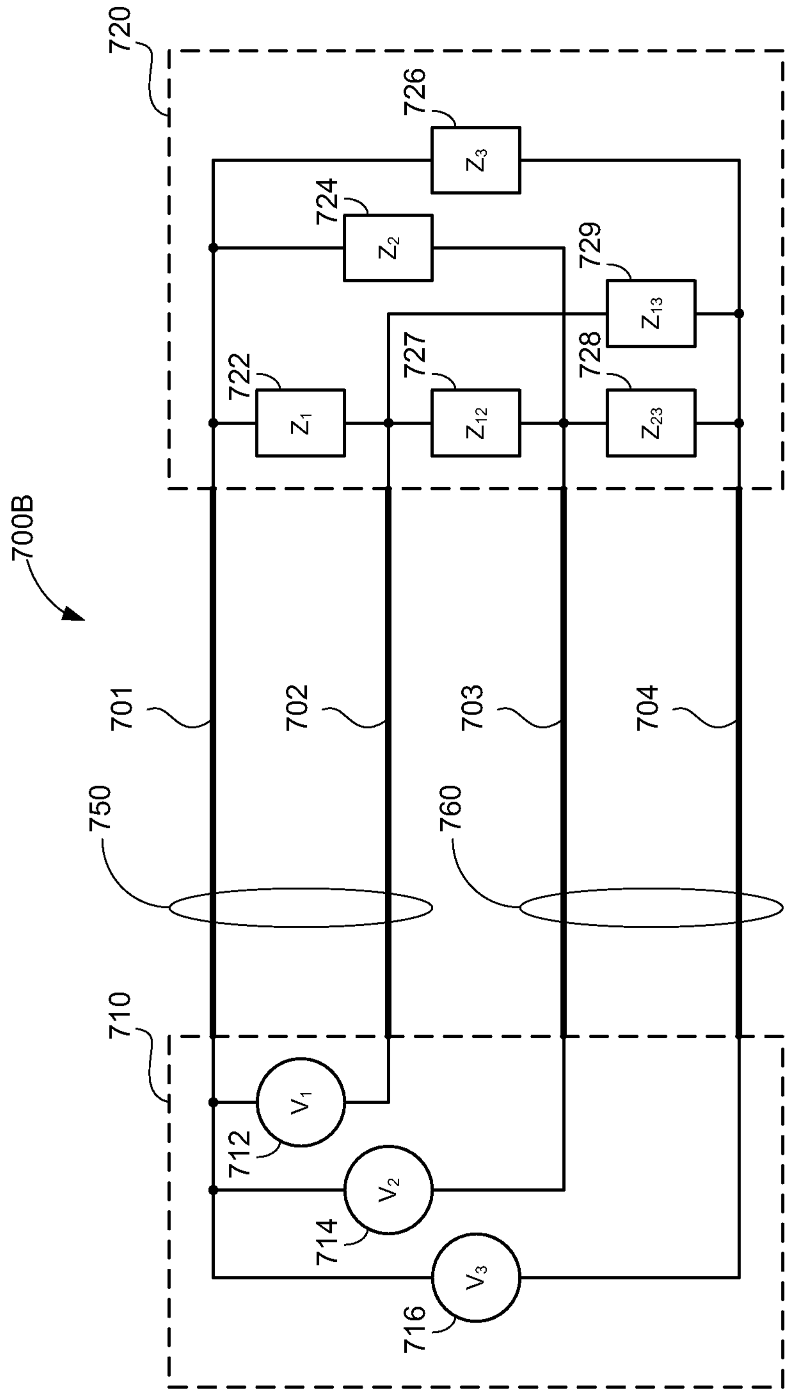

700B
720
726
724
729
722
727
728
701
702
703
704
750
760
710
712
714
716

FIG. 7B

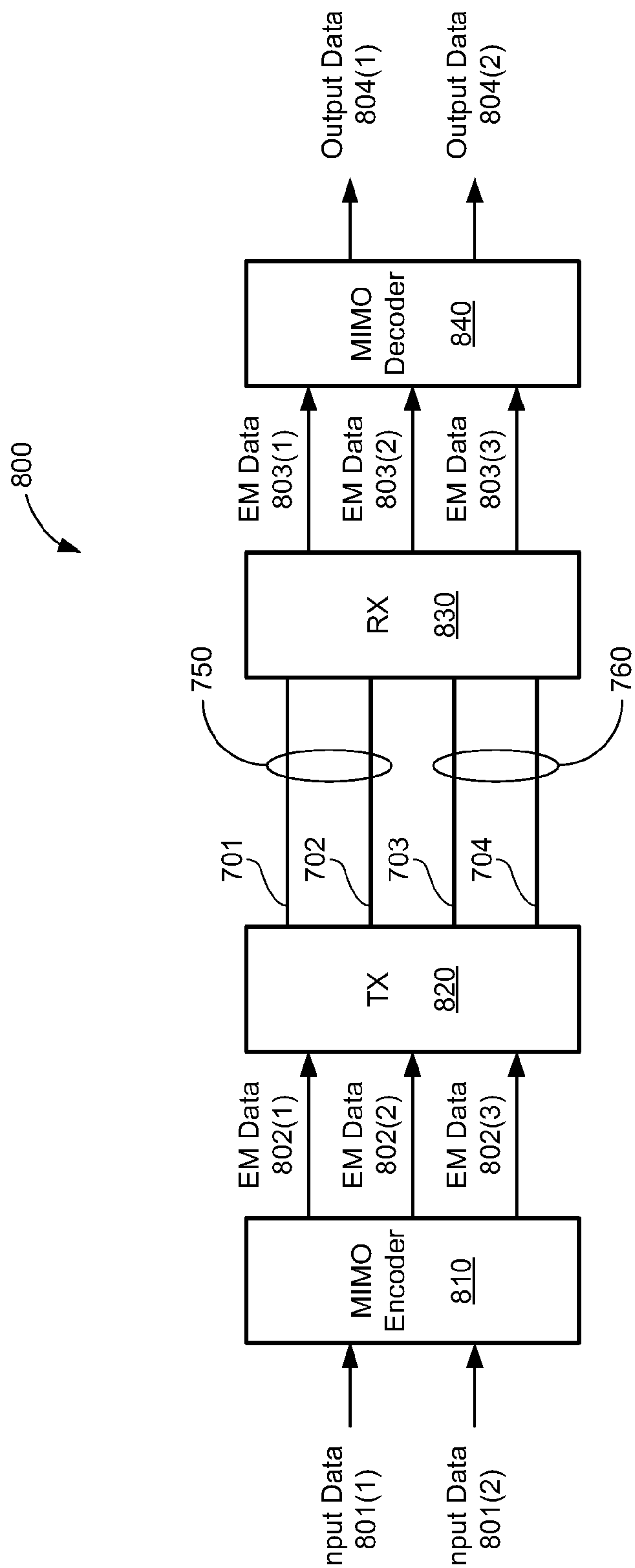

800
Input Data 801(1)
Input Data 801(2)
MIMO Encoder 810
EM Data 802(1)
EM Data 802(2)
EM Data 802(3)
TX 820
701
702
703
704
750
760
RX 830
EM Data 803(1)
EM Data 803(2)
EM Data 803(3)
MIMO Decoder 840
Output Data 804(1)
Output Data 804(2)

FIG. 8

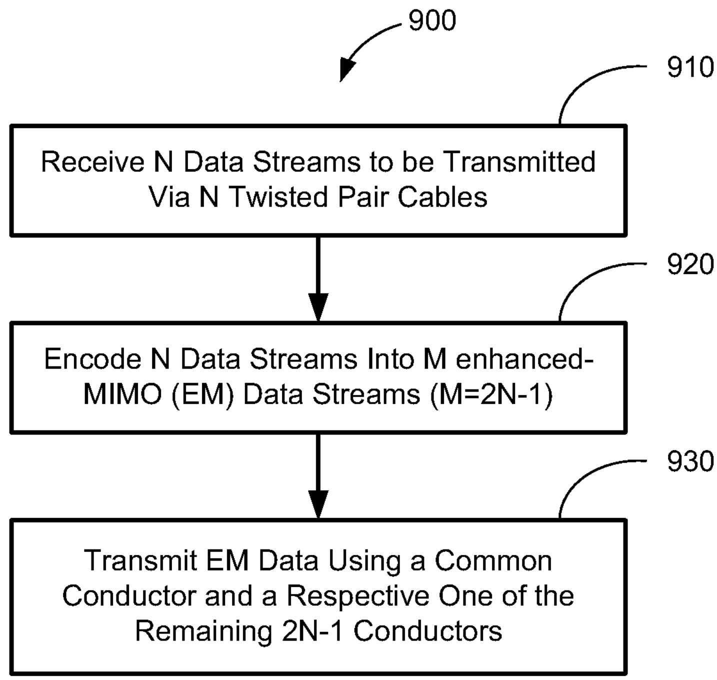

900
910
Receive N Data Streams to be Transmitted Via N Twisted Pair Cables
920
Encode N Data Streams Into M enhanced-MIMO (EM) Data Streams (M=2N-1)
930
Transmit EM Data Using a Common Conductor and a Respective One of the Remaining 2N-1 Conductors

FIG. 9A

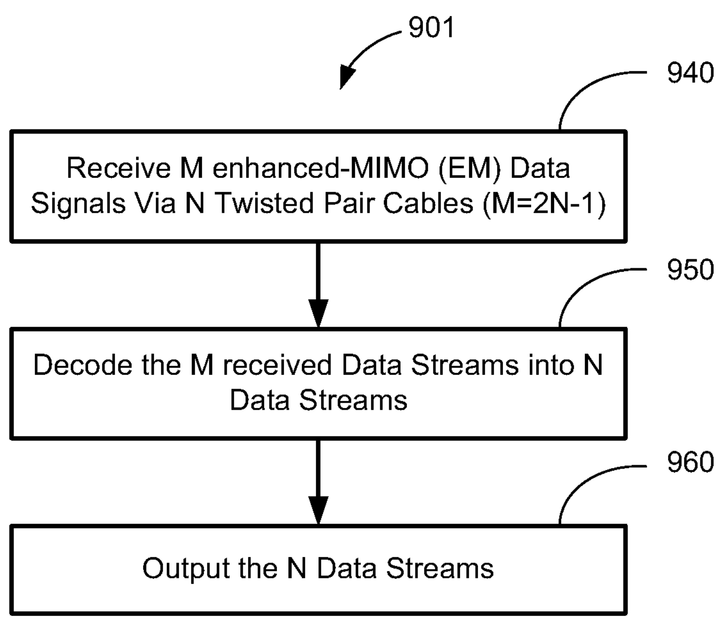

901
940
Receive M enhanced-MIMO (EM) Data Signals Via N Twisted Pair Cables (M=2N-1)
950
Decode the M received Data Streams into N Data Streams
960
Output the N Data Streams

FIG. 9B

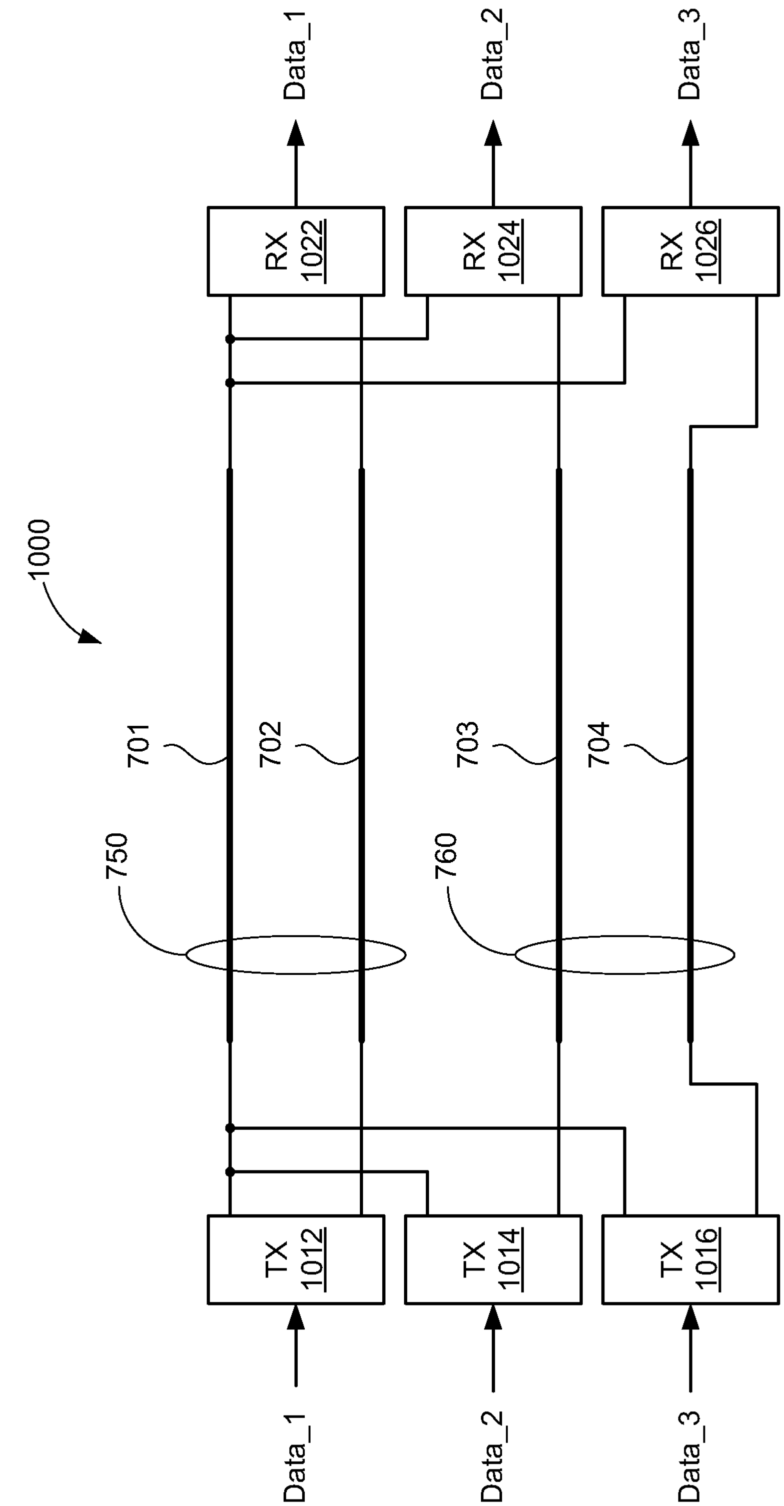

1000
Data_1
Data_2
Data_3
RX 1022
RX 1024
RX 1026
701
702
703
704
750
760
TX 1012
TX 1014
TX 1016
Data_1
Data_2
Data_3

FIG. 10

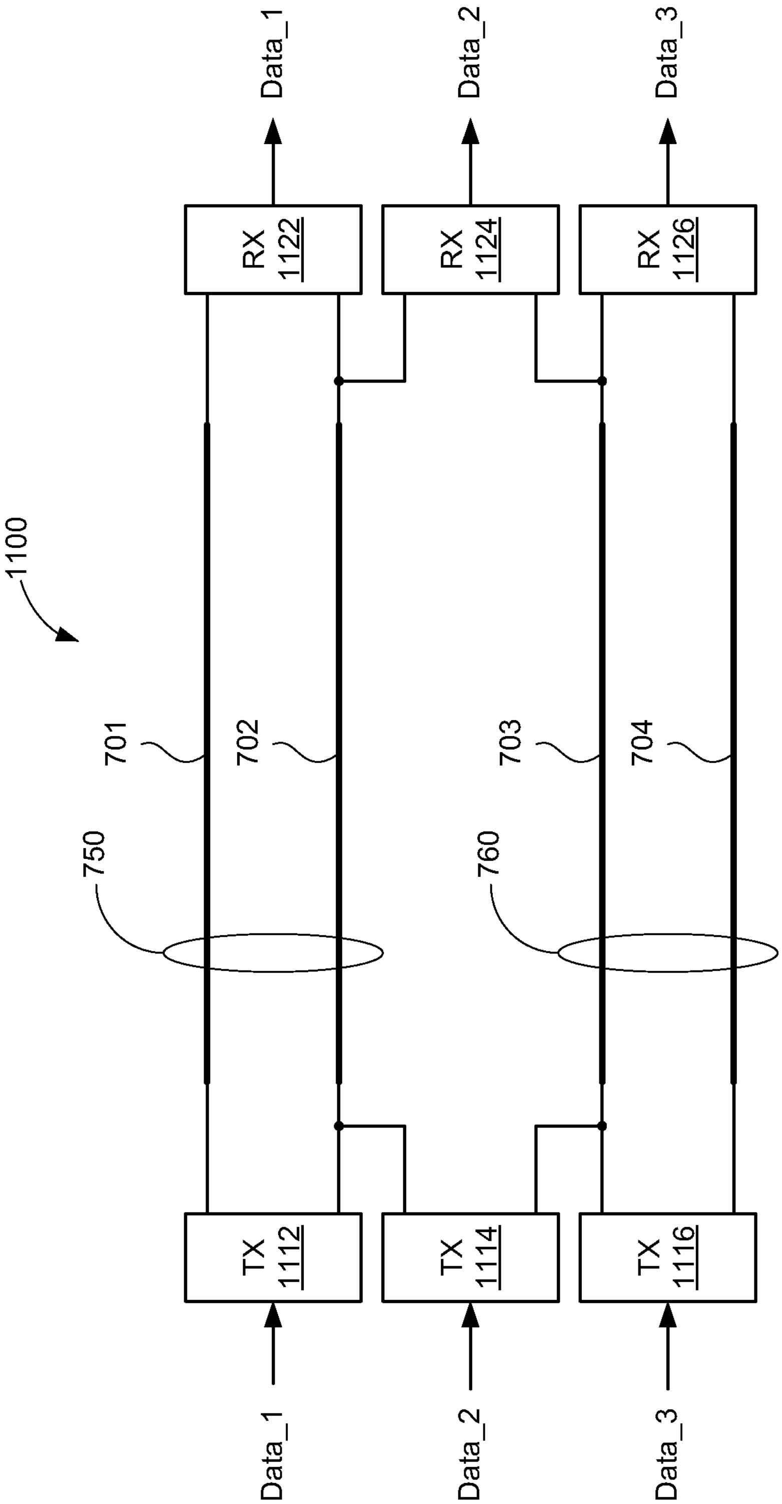
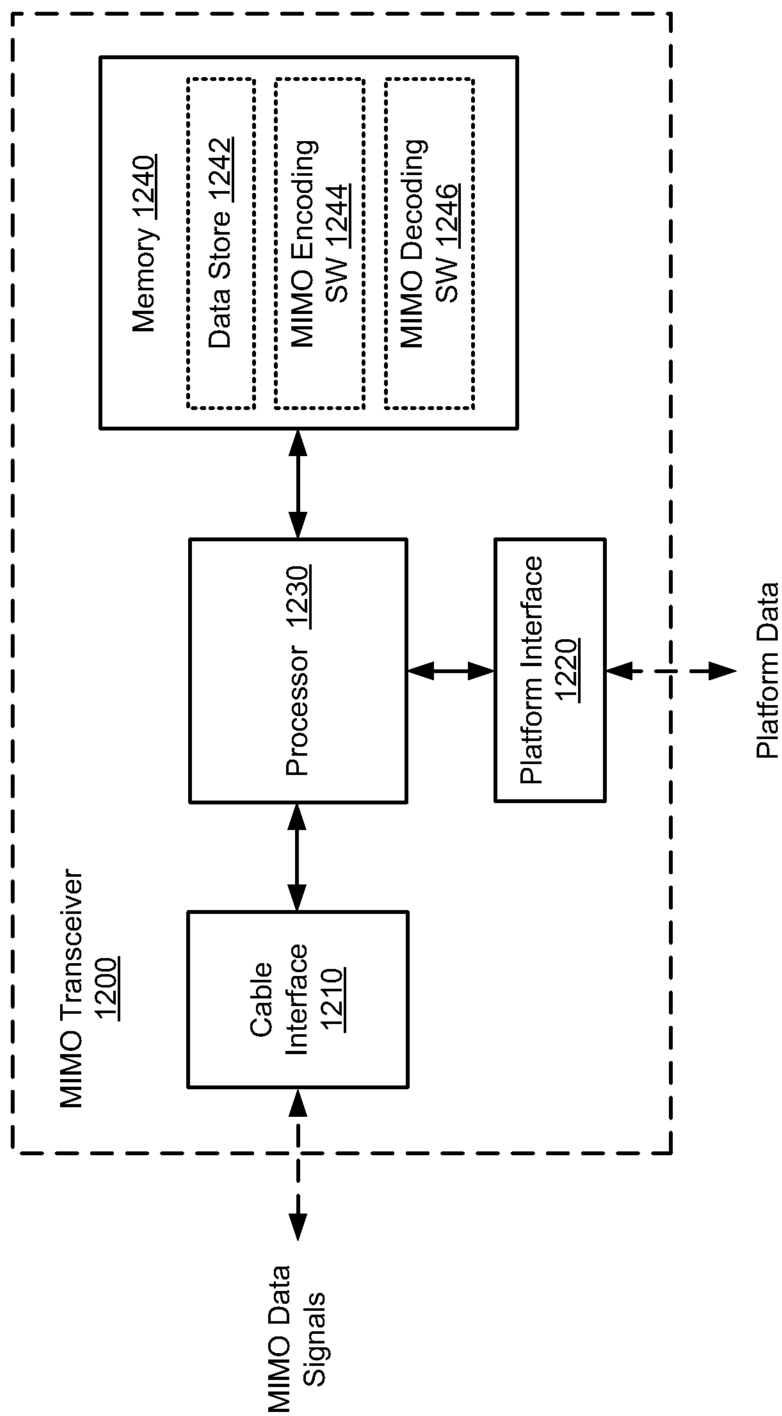

1100
Data_1
Data_2
Data_3
RX 1122
RX 1124
RX 1126
701
702
703
704
750
760
TX 1112
TX 1114
TX 1116
Data_1
Data_2
Data_3

FIG. 11



Memory 1240
Data Store 1242
MIMO Encoding SW 1244
MIMO Decoding SW 1246
Processor 1230
Platform Interface 1220
Platform Data
MIMO Transceiver 1200
Cable Interface 1210
MIMO Data Signals

FIG. 12

HIGHER ORDER MULTIPLE INPUT MULTIPLE OUTPUT IN ETHERNET

TECHNICAL FIELD

The present embodiments relate generally to twin-axial cables, and specifically to multiple-input and multiple-output (MIMO) signal transmission using twin-axial cables.

BACKGROUND OF RELATED ART

A twin-axial cable (or "twinax" cable) is a physical communication medium having two balanced inner conductors encapsulated by an outer shield. The two balanced inner conductors allow the twinax cable to be used for transmitting differential signals, while the outer shield isolates electrical signals carried on the inner conductors from external noise and interference. For example, FIG. **1** shows a conventional transmission configuration **100** for a twinax cable **110**. The twinax cable **110** includes a first inner conductor **101**, a second inner conductor **102**, and an outer shield **103**. Because the outer shield **103** isolates the inner conductors **101** and **102** from external noise and interference, it is typically coupled to ground potential. A voltage source **104**, coupled between the first inner conductor **101** and the second inner conductor **102**, generates differential signals for transmission through twinax cable **110**. Thus, twinax cable **110** may transmit a single set of data signals using differential signaling.

Because twinax cables are relatively inexpensive, they are becoming more widely used in modern high-speed differential signal transmission applications. For example, some 10G Ethernet systems transmit differential signals over twinax cables. Although fiber optic cables can provide faster data rates than copper-based mediums, fiber optic cables are expensive and may require additional front-end transceiver circuitry to implement within a network environment. Accordingly, there is a need for a cost-effective way to increase data transmission rates of twinax cables.

SUMMARY

This Summary is provided to introduce in a simplified form a selection of concepts that are further described below in the Detailed Description. This Summary is not intended to identify key features or essential features of the claimed subject matter, nor is it intended to limit the scope of the claimed subject matter.

A method and apparatus for concurrently transmitting multiple data signals on a single data cable are disclosed. The data cable includes at least a first inner conductor, a second inner conductor, and an outer conductive shield. For some embodiments, the cable may be a twin-axial (twinax) cable. In the present embodiments, a first data signal may be transmitted using the conductive shield and one of the first or second inner conductors, and a second data signal may be transmitted using the other (first or second) inner conductor that is not being used to transmit the first data signal. The first and second data signals may be transmitted concurrently.

For some embodiments, the second signal may be transmitted using the first and second inner conductors. The first data signal may be transmitted by applying a first voltage between the conductive shield and one of the first or second inner conductors. The second data signal may be transmitted by applying a second voltage between the first and second inner conductors. For some embodiments, the first data signals may be transmitted as differential signals, and the second data signals may be transmitted as single-ended signals.

For other embodiments, the first data signal may be transmitted using the conductive shield and the first inner conductor, and the second data signal may be transmitted using the conductive shield and the second inner conductor. The first data signal may be generated by applying a first voltage between the conductive shield and the first inner conductor. The second data signal may be generated by applying a second voltage between the conductive shield and the second inner conductor.

Further, for some embodiments, an encoder may receive a set of data intended for transmission via the first and second inner conductors. The encoder may then partition the set of data into first and second subsets, and generate the first and second data signals based on the first and second subsets of data, respectively.

Accordingly, the various signal transmission techniques described herein with respect to the exemplary embodiments may provide higher data rates for data cables than conventional data transmission techniques. In addition, at least some of the present embodiments may allow for more relaxed requirements on transceiver performance and/or cable loss when transmitting at lower data rates.

BRIEF DESCRIPTION OF THE DRAWINGS

The present embodiments are illustrated by way of example and are not intended to be limited by the figures of the accompanying drawings, where:

FIG. **1** is a cross-sectional illustration of a conventional transmission configuration for a twinax cable;

FIG. **2** is a cross-sectional illustration of a MIMO transmission configuration for a twinax cable in accordance with some embodiments;

FIG. **3** is a lumped parameter model illustrating one embodiment of a system for MIMO transmission over a twinax cable;

FIG. **4** is a block diagram illustrating one embodiment of a MIMO data transmission system employing twinax cables;

FIG. **5** is an illustrative flow chart depicting an exemplary operation for communicating MIMO signals over a twinax cable in accordance with some embodiments;

FIG. **6** is a cross-sectional illustration of a MIMO transmission configuration for a twinax cable in accordance with other embodiments;

FIGS. **7**A-**7**B illustrate MIMO transmission configurations for a cable including a set of twisted pairs, in accordance with some embodiments;

FIG. **8** is a block diagram illustrating an embodiment of a MIMO data transmission system employing twisted pairs;

FIGS. **9**A-**9**B are illustrative flow charts depicting exemplary operations for exchanging MIMO signals over a cable including a set of twisted pairs, in accordance with some embodiments;

FIG. **10** is a block diagram illustrating a more detailed embodiment of the MIMO data transmission system shown in FIG. **8**;

FIG. **11** is a block diagram illustrating another embodiment of the MIMO data transmission system shown in FIG. **8**; and

FIG. **12** is a block diagram of a MIMO transceiver in accordance with some embodiments.

DETAILED DESCRIPTION

In the following description, numerous specific details are set forth to provide a thorough understanding of the present disclosure. Also, in the following description and for purposes of explanation, specific nomenclature is set forth to provide a thorough understanding of the present embodiments. However, it will be apparent to one skilled in the art that these specific details may not be required to practice the present embodiments. In other instances, well-known circuits and devices are shown in block diagram form to avoid obscuring the present disclosure. The term "coupled" as used herein means connected directly to or connected through one or more intervening components or circuits. Any of the signals provided over various buses described herein may be time-multiplexed with other signals and provided over one or more common buses. Additionally, the interconnection between circuit elements or software blocks may be shown as buses or as single signal lines. Each of the buses may alternatively be a single signal line, and each of the single signal lines may alternatively be buses, and a single line or bus might represent any one or more of a myriad of physical or logical mechanisms for communication between components.

FIG. **2** is a cross-sectional illustration of a MIMO transmission configuration **200** for a twinax cable **210** in accordance with some embodiments. The twinax cable **210** includes a first inner conductor **201**, a second inner conductor **202**, and an outer conductive shield **203**. A first voltage source **204** is coupled between the first inner conductor **201** and the second inner conductor **202** of twinax cable **210**. A second voltage source **205** is coupled between the second inner conductor **202** and the conductive shield **203** of twinax cable **210**.

A first set of data signals (e.g., corresponding to a first subset of data) may be generated by first voltage source **204** and transmitted over twinax cable **210** using the two inner conductors **201** and **202**. More specifically, the first voltage source **204** may generate a first voltage V_{12} between the first and second inner conductors **201** and **202**. The first voltage V_{12} is thus translated into the first set of data signals. For some embodiments (e.g., wherein the first and second inner conductors **201** and **202** are substantially symmetrical), the first set of data signals may be transmitted on twinax cable **210** using differential signaling over the first and second inner conductors **201** and **202**.

A second set of data signals (e.g., corresponding to a second subset of data) may be generated by second voltage source **205** and transmitted over twinax cable **210** using the second inner conductor **202** and the conductive shield **203**. More specifically, the second voltage source **205** may generate a second voltage V_{2S} between the second inner conductor **202** and the conductive shield **203**. The second voltage V_{2S} is thus translated into the second set of data signals. For some embodiments, the second set of data signals may be transmitted via the second inner conductor **202** and the conductive shield **203** using single-ended (i.e., non-differential) signaling techniques. For example, the voltage of the conductive shield **203** may be used as a reference potential for voltages applied to the second inner conductor **202**. Alternatively, the voltage of the second inner conductor **202** may be used as a reference potential for voltages applied to conductive shield **203**.

Accordingly, the twinax transmission configuration **200** illustrated in FIG. **2** may allow for differential data signaling using the two inner conductors **201** and **202** concurrent with single-ended data signaling using the second inner conductor **202** and the conductive shield **203**. The ability to use conductive shield **203** as a transmission medium provides an additional degree of freedom, for example, as compared to coax cables and/or conventional twinax transmission techniques.

In addition, the twinax transmission configuration **200** of FIG. **2** may also relax the requirements on transceiver performance and cable loss, particularly at higher data rates. For example, if the bandwidth of twinax cable **210** is denoted as W, the total transmit power is denoted as P, and the additive white Gaussian noise with noise spectral density is denoted as N_0, then the upper bound on the achievable data rate (R_1) when using single-stream transmission techniques may be expressed as $R_1=W\log_2(1+P/N_0)$. In contrast, when using two-stream transmission techniques in accordance with some of the present embodiments (assuming each stream is transmitted as half of the power and ignoring inter-stream interference), then the upper bound on the achievable data rate (R_2) may be expressed as $R_2=2W\log_2(1+P/2N_0)$. Thus, when the signal to noise ratio (P/N_0) is high, then $R_2>R_1$. Alternatively, transmission techniques in accordance with some of the present embodiments may achieve the same data rate as single-stream transmission techniques (e.g., $R_2=R_1$) with either lower receiver noise (N_0) and the same total transmit power (P), or with lower total transmit power and the same receiver noise. Although the inter-stream interference may reduce transceiver gain for actual implementations of some of the present embodiments, interference suppression and/or cancellation schemes may be used to preserve the integrity of the multiple sets of data signals transmitted by some of the present embodiments.

For some embodiments, architectural similarities between twinax cable **210** of FIG. **2** and twinax cable **110** of FIG. **1** may allow transmission techniques of the present embodiments to be readily applied to legacy networks that employ conventional twinax cables. Moreover, although conductive shield **203** may be used for data transmission in accordance with the present embodiments, conductive shield **203** may also shield the inner conductors **201** and **202** from external noise and interference.

FIG. **3** is a lumped parameter model illustrating a MIMO transmission system **300** in accordance with some embodiments. The system **300** includes twinax cable **210**, a transmitter **310**, and a receiver **320**. Twinax cable **210** includes first inner conductor **201**, second inner conductor **202**, and conductive shield **203**. Transmitter **310** is coupled to one end of twinax cable **210**, and receiver **320** is coupled to the other end of twinax cable **210**. The transmitter **310** includes voltage sources **312** and **314** to transmit data signals to the receiver **320**. The receiver **320** includes detector circuits **322** and **324** to detect data signals received from the transmitter **310**.

In operation, the transmitter **310** may transmit a first data signal by causing the first voltage source **312** to generate a first voltage V_{12} between first and second inner conductors **201** and **202**. The transmitter **310** may transmit a second data signal by causing the second voltage source **314** to generate a second voltage V_{2S} between second inner conductor **202** and conductive shield **203**. The receiver **320** receives these data signals by detecting the voltages on the conductors **201**-**203**. For some embodiments (e.g., wherein the two inner conductors **201** and **202** are substantially symmetrical), the data signals transmitted by the first voltage source **312** may be a differential signal. Accordingly, the first detector **322** may detect the voltage V_1 on the first inner conductor **201** and add (or subtract) the voltage V_2 detected on the second inner conductor **202** to recover the first data signal. The second detector **324** may recover the second data signal transmitted via second inner conductor **202** and conductive shield **203** by detecting the voltage V_2 on the second inner conductor **202** with respect to the voltage V_S on the conductive shield **203**.

Note that, in the exemplary embodiment shown in FIG. **3**, the voltage V_2 on the second inner conductor **202** may be influenced by the voltage V_1 on the first inner conductor **201** and/or the voltage V_S on the conductive shield **203**. Nonetheless, at least two degrees of freedom may still be achieved using the system **300**. For example, because the transmitter **310** controls both voltage sources **312** and **314**, voltage source **314** may be biased such that the voltage V_S of the conductive shield **203** is held at a lower (or higher) potential than the voltage V_2 of the second inner conductor **202** to ensure that voltage signal V_{2S} may be detected by the second detector **324** while voltage signal V_{12} is detected by the first detector **322**. In some embodiments, the conductive shield **203** may be grounded (e.g., $V_S=0$). Alternatively, the transmitter **310** may selectively control each of the voltage sources **312** and **314** to ensure that the transmission of data using the two inner conductors **201** and **202** does not interfere with the transmission of data using the second inner conductor **202** and the conductive shield **203**.

For some embodiments, different waveforms may be generated for each of the two sets of data signals. For example, the first data signal may be transmitted using the two inner conductors **201** and **202** as a legacy baseband signal to maintain backward compatibility with legacy twinax systems, while the second data signal may be transmitted using the second inner conductor **202** and conductive shield **203** using other techniques (e.g., using OFDM symbols). Accordingly, for some embodiments, the receiver **320** may exploit different characteristics in the two sets of data signals to cancel or suppress cross-talk and interference between the signals. For other embodiments, the two sets of data signals may be transmitted using the legacy baseband signal. In either embodiment, the waveforms of the two signal streams may share the property that, in the frequency domain, their energy is allowed to cover the DC frequency. In some communication systems (such as DSL and powerline communications systems), data signals should not cover the DC frequency since the frequency band closest to DC is typically used for other purposes, for example, to carry a telephone signal and/or power. Under the present embodiments, the entire bandwidth (including DC) may be used for data signaling. In practice, it may be undesirable to use the DC frequency for carrying information due to possible heavy interference from the ambient environment. However, under present embodiments, even if a signal is carried in DC, no higher interference may be generated for other communications.

FIG. **4** is a block diagram of a MIMO transmission system **400** in accordance with other embodiments. The MIMO transmission system **400** includes a MIMO encoder **410**, a transmitter **420**, a receiver **430**, and a MIMO decoder **440**. A twinax cable **210**, including inner conductors **201** and **202** and conductive shield **203**, is coupled between the transmitter **420** and the receiver **430**. Note that, in some embodiments, transmitter **420** and receiver **430** may be replaced with transceivers that are configured to both transmit and receive data signals over twinax cable **210**. Such a configuration may allow for bidirectional communications via twinax cable **210**.

FIG. **5** is an illustrative flow chart depicting an exemplary operation **500** for communicating MIMO signals over a twinax cable in accordance with some embodiments. With reference, for example, to FIG. **4**, the MIMO encoder **410** first receives, as input, a set of data **401** to be transmitted, and encodes the data set **401** to produce two subsets of data **402(1)** and **402(2)** (**510**). The set of data **401** may be intended for transmission over the two inner conductors **201** and **202** of the twinax cable **210**, for example, using differential signal techniques. For some embodiments, the MIMO encoder **410** may partition the input data **401** into two subsets of data **402(1)** and **402(2)** which may then be transmitted over twinax cable **210** as two separate and/or parallel sets of data signals.

The transmitter **420** transmits the first subset of MIMO-encoded data **402(1)** (e.g., as a first set of data signals) using the two inner conductors **201** and **202** of twinax cable **210** (**520**). As discussed above, with respect to FIGS. **2** and **3**, the transmitter **420** may transmit the first set of data signals (e.g., as differential signals) by applying a voltage (V_{12}) between the two inner conductors **201** and **202**. The transmitter **420** further transmits the second subset of MIMO-encoded data **402(2)** (e.g., as a second set of data signals) using inner conductor **202** and conductive shield **203** (**530**). For example, as discussed above with respect to FIGS. **2** and **3**, the transmitter **420** may apply a second voltage signal (V_{2S}) between the second inner conductor **202** and the conductive shield **203** to transmit a second stream of data signals (e.g., as single-ended signals). For some embodiments, the first and second sets of data signals may be transmitted concurrently.

The receiver **430** receives a first subset of MIMO-encoded data **403(1)** (e.g., as the first set of data signals) via the inner conductors **201** and **202** of twinax cable **210** (**540**). For example, as described above with respect to FIG. **3**, the receiver **430** may receive the first subset of data **403(1)** by sampling the voltages between the first and second inner conductors **201** and **202**. The receiver **430** further receives the second subset of MIMO-encoded data **403(2)** (e.g., as the second set of data signals) via inner conductor **202** and conductive shield **203** of twinax cable **210** (**550**). For example, as described above with respect to FIG. **3**, the receiver **430** may receive the second subset of data **403(2)** by sampling the voltages between the second inner conductor **202** and the conductive shield **203**.

Finally, the MIMO decoder **440** decodes the two subsets of MIMO-encoded data **403(1)** and **403(2)** to produce a set of output data **404** (**560**). For example, the MIMO decoder **440** may combine the two subsets of MIMO-encoded data **403(1)** and **403(2)** to recover the originally-transmitted data. For some embodiments, MIMO encoder **410** and MIMO decoder **440** may be preconfigured to use the same encoding/decoding techniques. Alternatively, MIMO encoder **410** may transmit decoding instructions to the MIMO decoder **440** prior to, or concurrently with, the transmission of data.

The MIMO system **400**, as described above with reference to FIGS. **4** and **5**, may be implemented by replacing and/or adding circuitry to the front end of many legacy twinax applications. Accordingly, the MIMO system **400** may provide a low-cost technique for increasing the data rate of existing twinax communication systems.

FIG. **6** is a cross-sectional illustration of a MIMO transmission configuration **600** for twinax cable **210** in accordance with other embodiments. As described above, twinax cable **210** includes first and second inner conductors **201** and **202**, and conductive shield **203**. Furthermore, a first voltage source **604** is coupled between the first inner conductor **201** and the conductive shield **203**, and a second voltage source **605** is coupled between the second inner conductor **202** and the conductive shield **203**.

A first set of data signals may be transmitted via the first inner conductor **201** and conductive shield **203** using the first voltage source **604**, for example, by applying a first voltage V_{is} between the first inner conductor **201** and the conductive shield **203**. A second set of data signals may be transmitted via the second inner conductor **202** and conductive shield **203** using the second voltage source **605**, for example, by applying a second voltage V_{2S} between the second inner conductor **202** and the conductive shield **203**.

For some embodiments, the conductive shield **203** may be used as a common return path for data signals transmitted over each of the first and second inner conductors **201** and **202**. Although the inner conductors **201** and **202** may not be symmetrical with respect to the conductive shield **203**, the transmission paths of the two streams of data signals are nonetheless symmetrical. This makes impedance matching easier when transmitting two parallel data signals over twinax cable **210** using the transmission configuration **600** of FIG. **6**.

Furthermore, data transmitted via the first inner conductor **201** and conductive shield **203** may be represented as single-ended data signals. Similarly, data transmitted via the second inner conductor **202** and conductive shield **203** may also be represented as single-ended data signals. Thus, for some embodiments, the voltage on the conductive shield **203** may be pinned to ground since it may serve as the reference potential for the voltages on each of the first and second inner conductors **201** and **202**. This may allow an additional degree of freedom when using the conductive shield **203** for data signal transmission. For example, the transmission configuration **600** may transmit two substantially symmetrical sets of data signals in parallel, thus increasing the data rate of communications as compared to conventional twinax cable transmission techniques. In addition, the transmission configuration **600** may also relax the requirements on transceiver performance and cable loss, particularly at lower data rates (e.g., as described above with respect to FIG. **2**).

Note that the cutoff frequency for the transmission modes described above is assumed to be zero (e.g., DC). There may be multiple transmission modes at higher frequencies for data transmissions that utilize the conductive shield and at least one of the inner conductors **201** or **202**. At higher frequencies, multiple data signals may be transmitted concurrently over cable **210** at different directions of the electrical and magnetic fields. Thus, for some embodiments, one or more of the data transmission techniques described herein may be applied to co-axial ("coax") cables.

For example, in coax cables (and also for the data channel between one of the inner conductors **201** or **202** and conductive shield **203** in twinax cable **210**), for data transmitted at low frequencies (e.g., up to a few gigahertz), the corresponding signal wave propagates primarily in the transverse electric magnetic (TEM) mode. This means that the electric and magnetic fields are both perpendicular to the direction of propagation. However, above a certain cutoff frequency, transverse electric (TE) or transverse magnetic (TM) modes may also propagate in a manner similar to that in a waveguide. For conventional data transmission techniques, it is typically undesirable to transmit signals above the cutoff frequency because it may cause multiple modes with different phase velocities to propagate and therefore interfere with one another. However, when using advanced receiver techniques that suppress and cancel such interference, these higher modes may be used to reliably transmit data signals.

It should be noted that the foregoing embodiments are not limited to twinax cables. For example, MIMO transmission techniques described herein may be applied to tri-ax and/or quad-ax cables. Moreover, assuming a cable having N inner conductors, the transmission techniques described herein contemplate transmitting N concurrent data signals by leveraging the conductive shield of the cable as an additional conductor (e.g., as a transmit or return path). For example, the embodiment shown in FIG. **2** may be expanded to transmit N−1 concurrent data signals using the N inner conductors, whereby an additional data signal is further transmitted using the N^{th} inner conductor and the conductive shield. Similarly, the embodiment shown in FIG. **6** may be expanded to transmit N data signals, concurrently, using a respective one of the N inner conductors and the conductive shield to transmit each data signal.

In the embodiments described above, the inner conductors **201** and **202** of the twinax cable **210** may be very close in proximity to one another. Thus, cross-talk may be introduced between the channels when transmitting two streams of data in parallel. However, advanced receiver and/or transmitter techniques may effectively suppress, or even eliminate, such cross-talk. Examples of such receiver-side techniques include successive interference cancellation (SIC) and linear minimum-mean-square-error (LMMSE). In addition, the transmitter may provide a reference signal to the receiver.

More specifically, feedback about the channel conditions and/or the achievable rates of the two signal streams from the receiver **430** to the transmitter **420** may be provided. This feedback may be provided as the packet format to be used by the transmitter **420** and/or as an indicator of the channel quality. The feedback may also contain information about the relative phase between the two streams. The properly chosen relative phase may reduce the inter-stream interference, or the cross-talk between the streams. Under the same channel conditions, receivers **430** with different capabilities (e.g., a SIC receiver and an LMMSE equalizer receiver) may report different achievable rates to the transmitter **420**. This may be the case even for the same system and symmetric data signals (e.g., wherein each data signal is transmitted using one inner conductor and the conductive shield) because of the order of decoding performed by the SIC receiver. If the OFDM waveform is used for one or multiple signal streams, wherein the OFDM waveform is composed of multiple sub-bands, the feedback may contain information on the channel quality of each stream and relative phase between the two streams for each sub-band.

FIG. **7**A illustrates a MIMO transmission configuration **700**A for a cable including a set of twisted pairs **750** and **760**, in accordance with some embodiments. The first twisted pair **750** includes conductors **701** and **702**, and the second twisted pair **760** includes conductors **703** and **704**. The twisted pairs **750** and **760** are coupled between a transmitter **710** and a receiver **720**. The transmitter **710** includes a number of voltage sources **712**, **714**, and **716**. For some embodiments, the first voltage source **712** is coupled to the conductors **701** and **702**, the second voltage source **714** is coupled to the conductors **701** and **703**, and the third voltage source **716** is coupled to the conductors **701** and **704**. The receiver **720** includes a number of detector circuits **722**, **724**, and **726**. For some embodiments, the first detector **722** is coupled to the conductors **701** and **702**, the second detector **724** is coupled to the conductors **701** and **703**, and the third detector **726** is coupled to the conductors **701** and **704**.

A first set of data signals (e.g., corresponding to a first subset of data) may be generated by the first voltage source **712** and transmitted over the first twisted pair **750** (e.g., via the conductors **701** and **702**). More specifically, the first voltage source **712** may apply a first voltage V_1 across the conductors **701** and **702**. The first voltage V_1 is thus translated into the first set of data signals. The first detector **722** may receive the first set of data signals, via the conductors **701** and **702**, by detecting the current and/or voltage across a first load impedance Z_1. The first detector **722** may then recover the first data stream based on the detected current(s) and/or voltage(s). For some embodiments (e.g., wherein the conductors **701** and **702** are substantially symmetrical), the first subset of data may be transmitted on the twisted pair **750** using differential signaling techniques.

A second set of data signals (e.g., corresponding to a second subset of data) may be generated by the second voltage source **714** and transmitted via the conductors **701** and **703**. Specifically, the second voltage source **714** may apply a second voltage V_2 across the conductors **701** and **703**. The second voltage V_2 is thus translated into the second set of data signals. The second detector **724** may receive the second set of data signals, via the conductors **701** and **703**, by detecting the current and/or voltage across a second load impedance Z_2. The second detector **724** may then recover the second data stream based on the detected current(s) and/or voltage(s). For some embodiments, the second voltage source **714** transmits data signals using one of the conductors of the first twisted pair **750** (i.e., conductor **701**) and one of the conductors of the second twisted pair **760** (i.e., conductor **703**).

A third set of data signals (e.g., corresponding to a third subset of data) may be generated by the third voltage source **716** and transmitted via the conductors **701** and **704**. Specifically, the third voltage source **716** may apply a third voltage V_3 across the conductors **701** and **704**. The third voltage V_3 is thus translated into the third set of data signals. The third detector **726** may receive the third set of data signals, via the conductors **701** and **704**, by detecting the current and/or voltage across a third load impedance Z_3. The third detector **726** may then recover the third data stream based on the detected current(s) and/or voltage(s). For some embodiments, the third voltage source **716** transmits data signals using the shared conductor of the first twisted pair **750** (i.e., conductor **701**) and the remaining the conductor of the second twisted pair **760** (i.e., conductor **704**).

Because the conductor **701** is shared by (i.e., coupled to) all three voltage sources **712**, **714**, and **716**, the voltage level of the conductor **701** may be used as a common reference voltage by each of the voltage sources **712**, **714**, and **716** for generating their respective data signals. For some embodiments, the conductor **701** may be grounded. For other embodiments, the transmitter **710** may include circuitry to selectively control each of the voltage sources **712**, **714**, and **716** to ensure that the transmission of data by one voltage source does not interfere with the transmission of data by any of the other voltage sources.

Treating the conductors **701-704** as individual transmission lines provides an additional degree of freedom (e.g., allowing up to 3 data signals to be transmitted in parallel) as compared to, for example, conventional twisted pair transmission techniques. Furthermore, architectural similarities between twisted pairs cables described herein and prior art embodiments may enable the present embodiments to be readily applied to legacy networks that employ conventional twisted-pair cables (e.g., Category **5** and/or Category **6** cables).

In the embodiments described above, the conductors **701-704** of the twisted pairs **750** and **760** may be very close in proximity to one another. Thus, cross-talk may be introduced between the channels when transmitting multiple streams of data in parallel. Furthermore, signal reflections may also be introduced at the connections between the conductors **701-704** and the transmitter **710** and/or receiver **720**. Thus, for some embodiments, the transmitter **710** and/or receiver **720** may include impedance matching circuitry to mitigate such sources of signal interference.

For example, as shown in the configuration **700**B of FIG. 7B, the receiver **720** may include additional load impedances **727-729** that can be used to mitigate reflections and/or crosstalk in the conductors **701-704**. Specifically, the load **727** has an impedance value of Z_{12} and is coupled between the conductors **702** and **703**, the load **728** has an impedance value of Z_{23} and is coupled between the conductors **703** and **704**, and the load **729** has an impedance value of Z_{13} and is coupled between the conductors **702** and **704**. These load impedances **727-729**, in conjunction with the impedances associated with the detector circuits **722**, **724**, and **726**, can be used to match the impedance of the receiver **720** to the input impedances associated with the conductors **701-704**.

In addition to impedance matching, advanced receiver and/or transmitter techniques may effectively suppress, or even eliminate, cross-talk between conductors. Examples of such receiver-side techniques include successive interference cancellation (SIC) and linear minimum-mean-square-error (LMMSE). In addition, the transmitter **710** may provide a reference signal to the receiver **720** for purposes of detecting and mitigating external noise or interference.

It should be noted that the present embodiments have been described with respect to cables composed of two twisted pairs (e.g., twisted pairs **750** and **760**) for simplicity only. The enhanced MIMO transmission techniques described herein can be readily applied across any N number of twisted pairs. For example, the configurations **700**A and **700**B can be easily expanded to transmit 2N−1 data streams across N twisted pairs (e.g., using the 2N individual conductors that comprise the N twisted pairs, wherein one of the conductors is shared). Moreover, the N twisted pairs may be physically packaged into one or multiple cables.

FIG. **8** is a block diagram illustrating an embodiment of a MIMO data transmission system **800** employing twisted pairs. The system **800** includes a MIMO encoder **810**, a transmitter **820**, a receiver **830**, and a MIMO decoder **840**. Twisted pairs **750** and **760** are coupled between the transmitter **820** and the receiver **830**. FIGS. **9**A-**9**B are illustrative flow charts depicting exemplary operations **900** and **901** for exchanging enhanced MIMO signals over a set of twisted pairs in accordance with some embodiments. FIGS. **9**A-**9**B are described below with reference to the system **800** of FIG. **8**.

The MIMO encoder **810** initially receives N data streams of input data **801** to be transmitted via N twisted pairs (**910**). In a particular example, the MIMO encoder **810** may receive two data streams **801**(**1**) and **801**(**2**) that are intended to be transmitted over the twisted pairs **750** and **760**, respectively. For some embodiments, each of the N data streams may correspond to a differential data signal that is intended to be transmitted via a respective one of the N twisted pairs (e.g., using differential signaling). The MIMO encoder **810** then encodes (e.g., converts) the N data streams into M number of enhanced-MIMO (EM) data streams (**920**). For some embodiments, M=2N−1. For example, the MIMO encoder **810** may encode the two received data streams **801**(**1**) and **801**(**2**) into three EM data streams **802**(**1**)-**802**(**3**).

The transmitter **820** transmits the EM data using a common conductor and a respective one of the remaining 2N−1 conductors (**930**). More specifically, the transmitter **820** may generate data signals representing the EM data by applying a corresponding number of voltages across the conductors **701-704**. For some embodiments, the voltage level of one of the conductors **701-704** may be used as a common reference potential for biasing the remaining three conductors. For example, the transmitter **820** may transmit three EM data streams **802(1)-802(3)** by applying respective voltage biases between the conductor **701** and each of the remaining conductors **702-704**.

The receiver **830** receives M number of EM data signals via the N twisted pairs (**940**). More specifically, the receiver **830** may recover M number of EM data streams by detecting (e.g., sampling) the currents and/or voltages transmitted across the conductors **701-704**. For some embodiments, the voltage level of one of the conductors **701-704** may be used as a reference potential for determining the voltages on the remaining three conductors. For example, the receiver **830** may receive three EM data streams **803(1)-803(3)** by detecting respective voltage differences between the conductor **701** and each of the remaining conductors **702-704**.

The MIMO decoder **840** decodes (e.g., converts) the M received data streams into its original form, as N number of data streams (**950**), and outputs the decoded data streams for further processing (**960**). For example, the MIMO decoder **840** may receive three parallel streams of EM data **803(1)-803(3)** that represent two original data streams **804(1)** and **804(2)**. In other words, the three EM data streams **803(1)-803(3)** were originally intended to be transmitted as only two separate streams of data. The MIMO decoder **840** may thus reconstruct the original two data streams **804(1)** and **804(2)** from which the three EM data streams **803(1)-803(3)** were encoded.

Note that, in some embodiments, transmitter **820** and receiver **830** may be substituted for transceivers that are configured to both transmit and receive data signals over the conductors **701-704** (i.e., transceivers). Such a configuration may allow for bidirectional communications via the conductors **701-704**. Furthermore, the system **800** described above may be implemented by replacing or adding additional circuitry to the front end of many legacy twisted-pair cable (e.g., Cat **5** and/or Cat **6**) applications. Accordingly, the system **800** may provide a low-cost alternative for increasing the data rate of existing twisted pair-based communication systems.

FIG. **10** is a block diagram illustrating a more detailed embodiment of the MIMO data transmission system **800** shown in FIG. **8**. The system **1000** includes a number of transmitters **1012**, **1014**, and **1016** coupled to one end of twisted pairs **750** and **760**, and a number of receivers **1022**, **1024**, and **1026** coupled to the other end of the twisted pairs **750** and **760**. Specifically, the first transmitter **1012** and the first receiver **1022** are coupled to conductors **701** and **702**, the second transmitter **1014** and the second receiver **1024** are coupled to conductors **701** and **703**, and the third transmitter **1016** and the third receiver **1026** are coupled to conductors **701** and **704**.

In operation, the transmitters **1012**, **1014**, and **1016** receive data streams Data_**1**, Data_**2**, and Data_**3**, respectively, and output data signals representing the received data streams via the conductors **701-704**. For example, the data streams Data_**1**, Data_**2**, and Data_**3** may correspond to EM data streams encoded by a MIMO encoder (not shown). For some embodiments, each of the transmitters **1012**, **1014**, and **1016** may correspond to a transformer (e.g., balun transformer) that is capable of converting the received data stream onto a set of twisted-pair cable conductors. For example, the first transmitter **1012** may transmit the data stream Data_**1** via the conductors **701** and **702**, the second transmitter **1014** may transmit the data stream Data_**2** via the conductors **701** and **703**, and the third transmitter **1016** may transmit the data stream Data_**3** via the conductors **701** and **704**.

The receivers **1022**, **1024**, and **1026** are configured to recover the data streams Data_**1**, Data_**2**, and Data_**3**, respectively, by sampling the data signals carried by the conductors **701-704**. For some embodiments, each of the receivers **1022**, **1024**, and **1026** may correspond to a transformer that is capable of converting a data signal received over a set of twisted-pair cable conductors to a corresponding data stream. For example, the first receiver **1022** may recover the data stream Data_**1** from the conductors **701** and **702**, the second receiver **1024** may recover the data stream Data_**2** from the conductors **701** and **703**, and the third receiver **1026** may recover the data stream Data_**3** from the conductors **701** and **704**.

FIG. **11** is a block diagram illustrating another embodiment of the MIMO data transmission system **800** shown in FIG. **8**. More specifically, the system **1100** represents an alternative configuration for the system **1000** shown in FIG. **10**. For example, the system **1100** includes a first transmitter **1112** and a first receiver **1122** coupled to conductors **701** and **702**, a second transmitter **1114** and a second receiver **1124** coupled to conductors **702** and **703**, and a third transmitter **1116** and a third receiver **1126** coupled to conductors **703** and **704**.

As described above, with reference to FIG. **10**, each of the transmitters **1112**, **1114**, and **1116** and the receivers **1122**, **1124**, and **1126** may correspond to a transformer. Specifically, the first transmitter **1112** may transmit the data stream Data_**1** via the conductors **701** and **702**, the second transmitter **1114** may transmit the data stream Data_**2** via the conductors **702** and **703**, and the third transmitter **1116** may transmit the data stream Data_**3** via the conductors **703** and **704**. Similarly, the first receiver **1122** may recover the data stream Data_**1** from the conductors **701** and **702**, the second receiver **1124** may recover the data stream Data_**2** from the conductors **702** and **703**, and the third receiver **1116** may recover the data stream Data_**3** from the conductors **703** and **704**.

It should be noted that, in contrast with the system **1000** shown in FIG. **10**, no single conductor **701-704** is used as a common reference potential for the remaining conductors in the system **1100**.

FIG. **12** is a block diagram of a MIMO transceiver **1200** in accordance with some embodiments. The transceiver **1200** includes a cable interface **1210**, a platform interface **1220**, a local processor **1230**, and a memory **1240**. The cable interface **1210** is coupled to the processor **1230** and may be used to transmit and/or receive data signals over a data cable (e.g., twinax or twisted pair) in a manner prescribed by the processor **1230**. The platform interface **1220** is also coupled to the processor **1230** and may be used to communicate data to and/or from a computing platform (e.g., via a PCIe link).

Memory **1240** may include a data store **1242** that may be used to temporarily buffer data to be encoded and/or decoded. Furthermore, memory **1240** may also include a non-transitory computer-readable storage medium (e.g., one or more nonvolatile memory elements, such as EPROM, EEPROM, Flash memory, a hard drive, etc.) that can store the following software modules:

- a MIMO encoding module **1244** to encode outgoing data for MIMO-based transmission over a data cable; and
- a MIMO decoding module **1246** to decode MIMO-encoded data signals received over the data cable.

Each software module may include instructions that, when executed by the local processor **1230**, may cause the transceiver **1200** to perform the corresponding function. Thus, the non-transitory computer-readable storage medium of memory **1240** may include instructions for performing all or a portion of the operations described with respect to FIGS. **5** and **9**A-**9**B.

The local processor **1230**, which is coupled to the memory **1240**, may be any suitable processor capable of executing scripts of instructions of one or more software programs stored in the transceiver **1200** (e.g., within memory **1240**). For example, the processor **1230** can execute the MIMO encoding module **1244** and/or the MIMO decoding module **1246**.

The MIMO encoding module **1244** may be executed by the local processor **1230** to encode data signals to be transmitted over the data cable. For example, the MIMO encoding module **1244**, as executed by the local processor **1230**, may receive a set of data (e.g., from the computing platform) to be transmitted via the data cable, and encodes the data set to produce multiple subsets of data. For some embodiments, the processor **1230**, in executing the MIMO encoding module **1244**, may partition the received data set to be transmitted over the data cable as a plurality of separate and/or parallel sets of data signals. The processor **1230**, in executing the MIMO encoding module **1244**, may then transmit the data signals on the data cable such that at least one conductive element of the data cable is used in the transmission of two or more of data signals, concurrently (e.g., as described above with respect to FIGS. **5** and **9**A-**9**B).

The MIMO decoding module **1246** may be executed by the local processor **1230** to decode data received from a data cable. For example, the MIMO decoding module **1246**, as executed by the local processor **1230**, may receive a plurality of data signals, in parallel, over the data cable, and decodes the data signals to recover the originally-transmitted data set. For some embodiments, the processor **1230**, in executing the MIMO decoding module **1246**, may receive the data signals by sampling the voltages across each of the conductive elements of the data cable, wherein the voltage of at least one of the conductive elements is used as a common reference potential for determining the voltages associated with two or more data signals (e.g., as described above with respect to FIGS. **5** and **9**A-**9**B). The processor **1230**, in executing the MIMO decoding module **1246**, may then combine the received data signals in accordance with the encoding algorithm used by the MIMO encoding module **1244** to recover the original data set.

The various signal transmission techniques described herein with respect to the exemplary embodiments may provide higher data rates for data cables than conventional data transmission techniques. In addition, at least some of the present embodiments may allow for more relaxed requirements on transceiver performance and/or cable loss when transmitting at lower data rates. The present embodiments may be implemented in legacy data communications systems with little modification to the existing hardware infrastructure.

In the foregoing specification, the present embodiments have been described with reference to specific exemplary embodiments thereof. It will, however, be evident that various modifications and changes may be made thereto without departing from the broader scope of the disclosure as set forth in the appended claims. The specification and drawings are, accordingly, to be regarded in an illustrative sense rather than a restrictive sense. For example, the method steps depicted in the flow charts of FIGS. **5** and **9**A-**9**B may be performed in other suitable orders, multiple steps may be combined into a single step, and/or some steps may be omitted.

What is claimed is:

1. A method of data communication over a cable including at least a first inner conductor, a second inner conductor, and an outer conductive shield, the method comprising:

transmitting a first data signal using the conductive shield and the first inner conductor without using the second inner conductor; and

transmitting a second data signal using at least the second inner conductor.

2. The method of claim **1**, wherein the first and second data signals are transmitted concurrently.

3. The method of claim **1**, wherein transmitting the second data signal comprises:

transmitting the second data signal using the first and second inner conductors.

4. The method of claim **3**, wherein the second data signal is a differential signal, and wherein the first data signal is a single-ended signal.

5. The method of claim **3**, wherein the first data signal is transmitted by applying a first voltage differential between the conductive shield and the first inner conductor, and wherein the second data signal is transmitted by applying a second voltage differential between the first and second inner conductors.

6. The method of claim **1**, wherein transmitting the second data signal comprises:

transmitting the second data signal using the conductive shield and the second inner conductor.

7. The method of claim **6**, wherein the first and second data signals are single-ended signals.

8. The method of claim **7**, wherein the first data signal is transmitted by applying a first voltage differential between the conductive shield and the first inner conductor, and wherein the second data signal is transmitted by applying a second voltage differential between the conductive shield and the second inner conductor.

9. The method of claim **1**, further comprising:

receiving a set of data intended for transmission via the first and second inner conductors;

partitioning the set of data into a first subset of data and a second subset of data; and

generating the first and second data signals based on the first and second subsets of data, respectively.

10. A method of data communication over a cable including at least a first inner conductor, a second inner conductor, and an outer conductive shield, the method comprising:

receiving a first data signal via the conductive shield and the first inner conductor and not the second inner conductor; and

receiving a second data signal using at least the second inner conductor.

11. The method of claim **10**, wherein the first and second data signals are received concurrently.

12. The method of claim **10**, wherein receiving the second data signal comprises:

receiving the second data signal via the first and second inner conductors.

13. The method of claim **12**, wherein the second data signal is a differential signal, and wherein the first data signal is a single-ended signal.

14. The method of claim **12**, wherein the first data signal is received by detecting a first voltage differential between the conductive shield and the first inner conductor, and wherein the second data signal is received by detecting a second voltage differential between the first and second inner conductors.

15. The method of claim **10**, wherein receiving the second data signal comprises:

receiving the second data signal via the conductive shield and the second inner conductor.

16. The method of claim **15**, wherein the first and second data signals are single-ended signals.

17. The method of claim **16**, wherein the first data signal is received by detecting a first voltage differential between the conductive shield and the first inner conductor, and wherein the second data signal is received by detecting a second voltage differential between the conductive shield and the second inner conductor.

18. The method of claim **10**, further comprising:

decoding the first data signal and the second data signal to recover a first subset of data and a second subset of data, respectively; and

combining the first subset of data and the second subset of data to produce a single data stream.

19. A communications device, comprising:

an encoder coupled to a cable, the cable including at least a first inner conductor, a second inner conductor, and an outer conductive shield, wherein the encoder is to:

transmit a first data signal using the conductive shield and the first inner conductor without using the second inner conductor; and

transmit a second data signal using at least the second inner conductor.

20. The device of claim **19**, wherein the encoder is to transmit the first and second data signals concurrently.

21. The device of claim **19**, wherein the encoder is to transmit the second data signal using the first and second inner conductors, wherein the second data signal is a differential signal, and wherein the first data signal is a single-ended signal.

22. The device of claim **21**, wherein the encoder is to transmit the first data signal by applying a first voltage differential between the conductive shield and the first inner conductor, and wherein the encoder is to transmit the second data signal by applying a second voltage differential between the first and second inner conductors.

23. The device of claim **19**, wherein the encoder is to transmit the second data signal using the conductive shield and the second inner conductor, and wherein the first and second data signals are single-ended signals.

24. The device of claim **19**, wherein the encoder is to further:

receive a set of data intended for transmission via the first and second inner conductors;

partition the set of data into a first subset of data and a second subset of data; and

generate the first and second data signals based on the first and second subsets of data, respectively.

25. A communications device, comprising:

a decoder coupled to a cable, the cable including at least a first inner conductor, a second inner conductor, and an outer conductive shield, wherein the decoder is to:

receive a first data signal via the conductive shield and the first inner conductor and not the second inner conductor; and

receive a second data signal via at least the second inner conductor.

26. The device of claim **25**, wherein the decoder is to receive the first and second data signals concurrently.

27. The device of claim **25**, wherein the decoder is to receive the second data signal via the first and second inner conductors, wherein the second data signal is a differential signal, and wherein the first data signal is a single-ended signal.

28. The device of claim **27**, wherein the decoder is to receive the first data signal by detecting a first voltage differential between the conductive shield and the first inner conductor, and wherein the decoder is to receive the second data signal by detecting a second voltage differential between the first and second inner conductors.

29. The device of claim **25** wherein the decoder is to receive the second data signal via the conductive shield and the second inner conductor, and wherein the first and second data signals are single-ended signals.

30. The device of claim **25**, wherein the decoder is to further:

decode the first data signal and the second data signal to recover a first subset of data and a second subset of data, respectively; and

combine the first subset of data and the second subset of data to produce a single data stream.

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